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Precise marine positioning using the Global Positioning System (GPS).

Rahyono

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

PRECISE MARINE POSITIONING
USING
THE GLOBAL POSITIONING SYSTEM (GPS)

by

Rahyono

September 1985

Co-Advisors: Narendra K. Saxena
Stevens P. Tucker

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The development of the Global Positioning System (GPS) has led to the possibility of positioning marine platforms with great accuracy. This report describes position computations made from GPS observations aboard a ship and the evaluation of the accuracy and precision of a Texas Instruments TI-4100 GPS Receiver at sea in a low dynamic mode. The observed pseudoranges were corrected and smoothed by Doppler count, and then were used to compute position using an eight-state Kalman filter. A comparison is made between the ship's position obtained by GPS receiver and by

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The mean of the root-mean-square differences between launch positions determined by mean of GPS satellites and by Trisponder was found to be ± 11 m when four satellites were available and ± 21 m when only three were presents. Some 29 percent of the time, the GPS positions and Trisponders positions had similar accuracy.

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Precise Marine Positioning Using The Global Positioning System (GPS)

by

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I. INTRODUCTION

A. BACKGROUND

The art and science of marine positioning date back to antiquity, and have progressed from black magic, astronomical positioning, radar, Loran C and Omega to artificial satellite systems (Bresslau, 1980, pp. A35). The accuracy of land-based electronic systems varies: e.g., the Decca Pulse-8 system has an accuracy of ± 50 m at 200 nmi; Loran-C has an accuracy of ± 900 m at 2000 km (Laurila, 1976, pp. 348,429); Omega has an accuracy of ± 7.2 km globally (Creamer et al., 1985,pp. 269); while the Navy Navigational Satellite System has a 30-m accuracy with precise ephemerides for a single pass. In general the accuracies of electronic positioning systems are degraded by land propagation distortion (Laurila, 1976, pp. 502).

Astronomical navigation methods have serious observational limitations, i.e, the measurement depends on a plumb line and it is weather-sensitive, although a global datum is possible. The concept of positioning by an artificial satellite system began with the use of the Baker-Nunn camera for direction determination. This formed the foundation of real 3-dimensional positioning (Laurila, 1976, pp. 383).

The current operational navigation satellites are part of the U.S Navy Navigation Satellite System, usually called TRANSIT. The system was conceived in 1958 at the Applied Physics Laboratory of the Johns Hopkins University and became operational in January 1964 and commercially available in 1967. The technical approach was to use the Doppler shift to provide intermittent position fix updates (Laurila, 1976, pp. 463). The TRANSIT system consists of five operational satellites in polar orbits with altitudes of 1100 km, periods of 105 min, and frequencies of 150 MHz and 400 MHz. The satellites continuously broadcast predicted orbital coordinates along with timing signals, and are checked by four monitoring stations and two injection stations (Laurila, 1976, pp. 464).

In addition, the Department of Defense has been developing the Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR GPS) under the Joint Program Office (JPO) since 1973 as a merger of Navy's Time and Navigation (TIMATION), with Air Force Project 621B (Boissenin, 1985, pp. 1). The basic method of GPS/TRANSIT position fixing differs from conventional celestial navigation or visual satellite observation in that range, range-rate and angle are measured, since electronic systems do better in ranging than in angle measurement (Mueller, 1964, pp. 235-268; Easton, 1980, pp. 14). The TIMATION is a program to advance the development of high stability oscillators, time transfer, and two-dimensional navigation; Project 621b is to develop a highly accurate 3-dimensional navigation system (Boissenin, 1985, pp. 1).

The development approach for GPS selected by the Defense System Acquisition Review Council (DSARC) was a step-wise development and test program, leading in successive phases to an operational GPS. Each phase was designed to build and expand on the previous phase in an integrated and cohesive manner. The decision of DSARC I in December 1973 was to proceed with a phase I Concept and Validation to concentrate on validation of design concepts through Development Test and Evaluation (DT&E) of user equipment. The decision of DSARC II in June 1979 approved proceeding into full scale engineering development to complete the DT&E and Initial Operational Test and Evaluation (IOT&E) of user equipment. A DSARC III decision is planned for October 1985 to obtain Approval for Full Production (AFP) of the user equipment (Boissenin, 1985, pp. 2).

B. GPS POSITION AND NAVIGATION TECHNIQUE

The Global Positioning System (GPS) is a space-based radio positioning navigation system that is designed to provide continuous, highly accurate, three-dimensional position data to within a 16-m spherical error probability (SEP), velocity to within 0.05-0.10 m/s and system time to within 55 ns to suitably equipped users anywhere within 500 nmi of the earth. The position solution is based on World Geodetic System (WGS) 1972 ellipsoids in the Earth-Centered, Earth-Fixed (ECEF) coordinates. Accurate position and velocity determination will permit GPS to supplant less accurate systems such as Loran C, Omega, and Decca Pulse-8. GPS user equipment receives L-band signals from four satellites to measure pseudoranges and range-rates to solve for positions in three dimensions, velocity and time (Boissenin, 1985, pp. 2-3).

C. GPS CONFIGURATION

The GPS consists of space segments, control segments and user segments:

1. *Space Segment*

The space segment is composed of a constellation of satellites that continuously transmit signals to all users. When fully operational the GPS satellite constellation will deploy 18 satellites (plus 3 spares) in circular orbits at altitudes of 10900 nmi, inclined 45-65 deg, and having approximately 12-hr periods. The spacing of the satellites in their orbits will be arranged such that a minimum of four satellites will be available to a user anywhere on the globe (Boissenin, 1985, pp. 2; Jorgensen, 1984, pp. 1). Operational GPS satellites have projected mean mission durations of six years and design lives of seven and a half years (Senus and Heuerman, 1983, pp. 73).

The unperturbed orbit of satellites may be given by six Keplerian elements, namely the semi-major axis (a), eccentricity (e), mean anomaly (M) or time of perigee passage (T), right ascension of ascending node (Ω), inclination of orbital plane with respect to the equatorial plane (I), and argument of perigee (ω). The first three parameters determine the position of the satellite in its orbital plane, and the last three parameters determine the position of the orbital plane in the celestial coordinate system (Torge, 1980, pp. 115-119; Mueller, 1964, pp. 147-157).

The actual orbit of a satellite departs from the Keplerian model due to the effect of various disturbing gravitational forces and non-gravitational forces. The orbit can be viewed as oscillating ellipses which are given at each instant by the current orbital elements. The main gravitational forces are due to the earth, moon and sun. The earth's gravitational force depends on satellite position and time due to irregularities in the earth's density. The non-gravitational forces are due to solar radiation pressure, magnetic effects, atmospheric drag, and relativity. The actual orbit can be modeled by the initial six Keplerian elements plus time (t), ellipsoidal harmonic coefficients (zonal harmonic J, tesseral harmonics J and K), and their rates of change (Torge, 1980, pp. 116-117; Heiskanen and Moritz, 1967, pp. 342-345). The computation of satellite position by ellipsoidal harmonic coefficients needs sophisticated software in the receiver (MacDoran et al., 1984, pp. 65).

The actual orbit can be modeled also by the initial six Keplerian elements, secular drift terms and harmonic coefficients to reduce computation. Such a model, however, requires continuous updating. As applied in the current GPS, corrections are uploaded to satellites every 24 hours by the master station, and these are used to make hourly changes on board the satellite (MacDoran et al., 1984, pp. 65).

GPS satellites simultaneously transmit navigation information on two radio frequencies, L1 and L2. The L1 signal is modulated with C/A code (C/A = coarse-acquisition) and a P-code (P = precission), and the L2 signal is modulated with the P-code only. The functions of the codes are to identify the particular satellite and to measure phase shifts; both are necessary to measure pseudoranges. Both the L1 and L2 signals are also continuously modulated with the navigation data bit stream at 50 bps (Remondi, 1984, pp. 2; Milliken and Zoller, 1980, pp. 6). Due to different gravitational potentials on the ground and at the satellite, and to velocities of users relative to the satellites, the satellites actually transmit a slightly lower frequency ($\Delta f = 4.45 \times 10^{-10}$ so that 10.22999999545 MHz is shifted to a nominal 10.23 MHz (Spilker, 1980, pp. 33). The navigation message contains information on the status of the satellite, the time synchronization information for transfer from C/A- to P-code, the parameter for computation of the clock correction, the ephemerides for computation of satellite position, the parameter for propagation delay correction, and the almanac for computing Geometric Dilution of Precession (GDOP)/satellite selection. The navigation message is intended to keep the satellite ephemerides and timing system as accurate as possible (Milliken and Zoller, 1980, pp. 7; Van Dierendonck et al., 1980, pp. 576). The contribution of satellite segment errors was monitored during the GPS development phase, and the recorded bias errors were found to be for X, -2 to -4 m; for Y, -5 m; and for Z, ±3 m (JPO, 1984, pp. 6).

2. *Control Segment*

The control segment tracks all satellites in orbit. The purpose of satellite tracking is to observe the position and motion of a satellite as a function of time with a precision sufficient to refine its equation of motion to permit predicting future position with at least the accuracy achievable by direct observation. The operational control segment consists a master control station, a ground control station, monitor stations and an alternate control station. The monitor stations collect atmospheric and satellite tracking data from all satellites in view, which are encrypted and transmitted to the master control station, the ground control station and the alternate control station (Boissenin, 1985, pp. 2). The master control station uses one week's data from all monitor stations to control the satellites' health, to generate new satellite ephemerides and clock offset updates, and then transmit these updates to the constellation of satellites every 24 hours (Milliken and Zoller, 1980, pp. 69).

3. *User Segment*

The fundamental capabilities of the GPS user segment are satellite selection, signal acquisition, tracking and measurement, data recovery, and data processing for the real time user. The hardware component is comprised of an antenna, a receiver, and input/output devices (Glazer, 1980, pp. 81).

If a GPS receiver has a very accurate clock synchronized precisely with the satellite clock, it can measure the transit time of the signal between the satellite and the receiver and multiply this by the speed of light to get the range from receiver to satellite. Due to expense and the impracticality of maintaining a synchronized clock at both the satellite and the receiver, only a crystal clock is used in the receiver, so that the measured signal transit time is subject to receiver clock error. This uncorrected distance is called the pseudorange. By measuring four pseudoranges to different satellites, the user's position can be calculated in the ECEF World Geodetic System 1972, which may then be transformed to another datum (Milliken and Zoller, 1980, pp. 3-4).

As the satellite signals vary, one can exploit each signal by various means to get a position. At present there are two methods: The first uses the code signal to measure pseudorange and pseudorange rate; and the second uses the uncoded transmission signal as a source for very-long-base-line interferometry (VLBI). Boissenin (1985), Buennagel et al., (1984), Bock et al., (1984), Borel (1980), MacDoran (1984), JPO (1984), and Glazer (1980) provide detailed information on the uncoded GPS receivers.

The Texas Instruments TI-4100 GPS receiver uses both C/A-code and P-code systems. It is a single-channel, two-frequency, digitized multiplexing receiver, capable of tracking simultaneously up to four satellites with continuous L1 and L2 frequency measurement. Lock-on for each signal is for 5 ms, for a total of 40 ms to complete one sequence (Johnson et al., 1984, pp. 61). The receiver clock permits connection to an external atomic clock so that the minimum number of satellites needed is reduced to three. The standard receiver unit consists of an antenna and pre-amplifier, a control display unit and a dual cassette recorder. The antenna assembly consists of a conical omni-directional antenna and the pre-amplifier. The Control Display Unit is a hand-held input/output device with alphanumeric displays (TI-4100, 1983, pp. 1-4 to 1-7).

Data acquired with a TI-4100 receiver were used in this study which involved processing pseudorange data into position data and comparing GPS-determined positions with Trisponder-determined position data. The field data were acquired by the U.S Naval Oceanographic Office (NAVOCEANO) in Mississippi Sound. The development of the computer programs was very slow due to a large data set that was very difficult to handle; however, a mathematical model was developed. Calculations were actually made at the Naval Surface Weapon Center (NSWC) using NSWC computer programs written by S.L. Meyerhoff because the NSWC computer programs were found to be incompatible with the NPS IBM-3033; nor was it possible to get the NSWC computer program to run on the Fleet Numerical Oceanography Center's Cyber-175. The NSWC least squares adjustment program was more sophisticated than the one I developed in that it included a combination of bias Doppler data, bias frequency of the satellite's clock, and bias frequency of the receiver's clock.

II. MATHEMATICAL MODEL USED IN THE POINT POSITIONING MODE

The mathematical model may be divided into two parts, namely determination of coordinates in WGS 1972, and transformation to geodetic coordinates in some other datum. For this evaluation, the comparison between launch positions determined by Trisponders and by GPS is done in UTM, so a transformation of coordinates is performed for the shore station.

To get good accuracy the relative geometry of the satellites and the ground receiver must be good. This geometry is calculated by the Geometric Dilution of Position (GDOP) method. The unknown position of the receiver's antenna (X, Y, Z coordinates) and receiver's clock offset are functions of four satellite positions and four corrected pseudoranges. The satellites' positions are calculated from ephemerides. The receiver measures four observed pseudoranges to different satellites which must be corrected for atmospheric delay, relativity, earth rotation and satellite clock offset. The four unknown parameters of the receiver are calculated either by the conventional iterative least squares method or the Kalman filter method. Meyerhoff (1985), has developed computer programs to calculate either by least squares adjustment or Kalman filter methods. The formulas used for the computations in the computer program will be mentioned only here; their derivations can be found in the references.

A. SATELLITE SELECTION

If more than four satellites are above the user's horizon, the receiver can select the best geometry to get the best position, otherwise satellite selection is made on the basis of the satellites' health and the ages of the data messages. The geometric dilution of position (GDOP) is a measurement of the best geometry, which is a function of the user's and the satellite's position. The satellite's coordinates are computed from the almanac. The parameters of the almanac are simplified ephemerides parameters and are stored in the receiver's memory or can be entered by the operator; the formula used is similar to that developed in Subchapter C below. The computation of GDOP is performed in the receiver by the following formula:

$$\text{GDOP} = [\text{Trace }(A\ A)^{-1}]^{1/2} \tag{2.1}$$

$$A = \begin{vmatrix} \cos\alpha_x^1 & \cos\alpha_y^1 & \cos\alpha_z^1 & 1 \\ \cos\alpha_x^2 & \cos\alpha_y^2 & \cos\alpha_z^2 & 1 \\ \cos\alpha_x^3 & \cos\alpha_y^3 & \cos\alpha_z^3 & 1 \\ \cos\alpha_x^4 & \cos\alpha_y^4 & \cos\alpha_z^4 & 1 \end{vmatrix}$$

$\cos\alpha_x^k$ = direction cosines of the angles between the range to satellite number k and the x axis.

An acceptable range is $2 \le \text{GDOP} \le 4$ (Jorgensen, 1984, pp. 9-10).

B. PSEUDORANGE

The pseudorange corrections and satellite's clock offset are calculated and applied to the observed pseudoranges to get corrected pseudoranges (Milliken & Zoller, 1980, pp. 4; Spilker, 1980, pp. 24).

$$R_{obs} = R_{tru} + c[t_c + (\delta t_u - \delta t_s)] \tag{2.2}$$

R_{obs} = pseudo-range observed to SV [m]

R_{tru} = true range user to SV [m]

SV space vehicle

t_c = time correction consist of atmospheric, relativity, and earth rotation [s]

δt_s = SV clock offset from GPS time [s]

δt_u = user clock offset from GPS time [s]

c = velocity of light [m/s]

The computation of satellite clock offset from GPS time is done by a polynomial model (Equation 2.4), given by Meyerhoff (1985) and Van Dierendonck et al. (1980). The model's parameters and the time reference of the parameters are given in the navigation messages. The receiver's clock offset from the GPS time, is included in the four unknown receivers' parameters.

$$t_{tag} = t_{ts} - \delta t_{sv} \tag{2.3}$$

δt_{sv} = clock offset correction of SV [s]

t_{tag} = GPS time tag of measurement [s]

t_{ts} = the space vehicle code phase time at message transmission time [s]

$$\delta \hat{t}_{sv} = a_o - a_1(t_{tag} - t_{oe}) + a_2(t_{tag} - t_{oe})^2 \tag{2.4}$$

a_o = parameter of clock satellite bias [s]

a_1 = parameter of clock satellite drift [s/s]

a_2 = parameter of clock satellite aging [s/s²]

t_{oe} = reference time of clock drift at GPS system time [s]

The pseudorange correction consists of corrections due to atmospheric, relativity and earth rotation effects. Formulas for these are given in this section. The atmospheric correction may be separated into an ionospheric correction and a tropospheric correction (Equation 2.5). The ionospheric correction depends on the electron contents of the atmosphere. The best ionospheric correction formula uses observations of pseudorange at two frequencies L1 and L2. Equation 2.6 is used in the computation. The ionospheric correction may be calculated by an ionospheric model included in the satellite navigation messages; this polynomial model is less accurate than Equation 2.6, and was not used in this evaluation. If the P-code is not available, however, Equation 2.6 can't be used.

$$t_{atm} = t_{ion} + t_{trop} \tag{2.5}$$

The ionospheric correction for pseudoranges is given by Equation 2.6 (Spilker, 1980, pp. 25), and the ionospheric correction for pseudorange rates by Equation 2.7 (Meyerhoff, 1985, pp. 20).

$$t_{ion} = 1.5336\ \delta t_{gdL1} \tag{2.6}$$

t_{ion} = ionospheric correction [s]

δt_{gdL1} = difference between propagation at L1 and L2 [s]

$$t_{ionrd} = \frac{(\gamma_1 / Q_1 - \gamma_2 / Q_2)}{[(Q_1 / Q_2)^2 - 1]\ \psi} \tag{2.7}$$

t_{ionrd} = ionospheric Doppler correction [s]

γ_1 = L1 Doppler count

Q_1 = L1 frequency multiplier = 154

γ_2 = L2 Doppler count

Q_2 = L2 frequency multiplier = 120

ψ = Nominal satellite frequency = 10,230,000 Hz

The tropospheric correction is computed by the Chow model tropospheric correction given in Equation 2.8 (Meyerhoff, 1985, pp. 22-24).

$$t_{trop} = \frac{0.0276\ P}{[\sin\theta\ (\tan\theta + 0.0045) + 0.00143]} + \frac{470\ T^2\ E^{1.23} + 1.705\ 10^6\ \rho}{[T^3 \sin\theta\ (\tan\theta + 0.017) + 0.00035]} \tag{2.8}$$

E = 35.65 H 10

P = surface pressure [mbar]

T = temperature [°K]

ρ = temperature lapse rate set at .006 [deg/m]

H = percent relative humidity

θ = elevation angle of satellite [deg]

The relativity corrections (t_{rel}) due to the eccentricity of the satellite's orbit, are computed by Equation 2.9 (Meyerhoff, 1985, pp. 27-28):

$$t = \frac{2\ e \sin E\ \mu^{1/2}\ A^{1/2}}{c} \quad (2.9)$$

t_{rel} = relativity correction [s]

e = eccentricity of satellite orbit

E = eccentric anomaly (it could be solved iteratively)

μ = WGS-72 value of the earth's universal gravitational constant = 3.986008 10^{14} [m^3/s^2]

A = semi major axis of orbit [m]

c = speed of light in vacuum [m]

The earth rotation corrections (t_{rot}) due to the motion of the earth during the signal's propagation, are computed by Equation 2.10 (Meyerhoff, 1985, pp. 25-26]:

$$t_{rot} = \dot{\Omega}_e\ (\ Y_{sat}X_o\ -\ X_{sat}Y_o) \quad (2.10)$$

$\dot{\Omega}_e$ = WGS-72 value of the earth's rotational rate = 0.00007292115147 [rad/s]

$X_{sat} Y_{sat}$ = ECEF of satellite coordinates, WGS-72 [m]

X_o, Y_o = ECEF coordinates of the station, WGS-72 [m]

C. SATELLITE POSITION CALCULATION

To compute a ship's position, the satellite position must be computed from the ephemerides transmitted in the navigation messages. As the satellite ephemerides parameters are Keplerian elements in secular drift terms and harmonic coefficients only, the receiver does not need sophisticated software to compute the satellite position. It must be noted, however, that the parameters change every hour. The computed mean motion was solved by Kepler's third law. The Keplerian parameters (mean anomaly, argument of latitude, radius of orbital plane, and longitude of ascending node) are affected by secular drift terms and harmonic coefficients, which must be corrected from their value at reference time by their drift. The drift of each parameter is a function of the time from epoch and secular drift plus harmonic corrections. A sample computation of satellite position may be found in Mueller (1964).

1. *Conversion of Receiver Time to GPS Time*

The GPS position is marked by the receiver clock; however, the reference time for satellite position computation is GPS system time. The receiver time tag must be converted to the GPS system time by the following step.

$$t_{tag} = t_{rec} - \delta t_u - t_{tran} \tag{2.11}$$

t_{tag} = GPS system time at time of transmission; GPS time of reception corrected for transit time [s]

t_{rec} = receiver time tag at receiver clock [s]

δt_u = receiver time offset from GPS system time originally set to zero, it is included in the unknown parameter [s]

t_{tran} = transit time of signal from satellite to user [s]

The time from epoch is related to the ephemerides reference time by:

$$t = t_{tag} - t_{oe} \tag{2.12}$$

t = time from epoch, if greater than 302,400 subtract 604,800; if less than -302,400 add 604,800 [s]

t_{oe} = ephemerides reference time at GPS system time [s]

2. *Computation of Orbital Plane Parameters*

The orbital plane parameter is computed by Kepler's third law (Equation 2.13) and Kepler's first law (Equation 2.16). The WGS-72 parameters for the computation are:

μ = WGS-72 value of the earth's universal gravitational constant = $3.986008\ 10^{14}$ [m^3/s^2]

$\dot{\Omega}_e$ = WGS-72 value of the earth's rotational rate = 0.00007292115147 [rad/s]

The mean motion is affected primarily by secular drift terms; (Van Dierendonck, 1980, pp. 67) it is corrected as follows:

$$n_o = \frac{\mu^{1/2}}{A^{3/2}} \tag{2.13}$$

n_o = computed mean motion [rad/s]

A = semi major axis of orbit [m]

$$n = n_o + \delta n \tag{2.14}$$

n = corrected mean motion [rad/s]

δn = mean motion difference from computed value

$$M = M_o + n\,t \tag{2.15}$$

M = mean anomaly [rad]

M_o = mean anomaly at reference time [rad]

The eccentric anomaly was computed by:

$$M = E + e \sin E \tag{2.16}$$

E = eccentric anomaly (it could be solved iteratively)

e = eccentricity of satellite orbit

3. *Computation of Orbital Plane Parameters in ECEF*

The orbital plane parameters in ECEF are affected by secular drift terms and harmonic coefficients; these effects were calculated as corrections to the parameters as follows:

$$\cos \nu = (\cos E - e)/(1 - e \cos E) \tag{2.17}$$

$$\sin \nu = [\sin E \,(1 - e^2)] / (1 - e \cos E) \tag{2.18}$$

ν = true anomaly [rad]

$$\phi = \nu + \omega \tag{2.19}$$

ϕ = argument of latitude [rad]

ω = argument of perigee [rad]

$$\delta U = C_{uc} \cos 2\phi + C_{us} \sin 2\phi \tag{2.20}$$

δU = argument of latitude correction [rad]

C_{uc} = amplitude of the cosine harmonic correction to the argument of latitude [rad]

C_{us} = amplitude of the sine harmonic correction to the argument of latitude [rad]

$$\delta r = C_{rc} \cos 2\phi + C_{rs} \sin 2\phi \tag{2.21}$$

δr = radius correction [m]

C_{rc} = amplitude of the cosine harmonic correction term the orbit radius [m]

C_{rs} = amplitude of the sine harmonic correction term the orbit radius [m]

$$\delta I = C_{ic} \cos 2\phi + C_{is} \sin 2\phi \tag{2.22}$$

δI = correction to inclination [rad]

C_{ic} = amplitude of the cosine harmonic correction term the angle of inclination [rad]

C_{is} = amplitude of the sine harmonic correction term the angle of inclination [rad]

$$U = \phi + \delta U \tag{2.23}$$

U = corrected argument of latitude [rad]

$$r = A\,(1 - e \cos E)^{1/2} + \delta r \tag{2.24}$$

r = corrected [m]

$$I = I_o + \delta I \qquad (2.25)$$

I = corrected inclination [rad]

I_o = inclination angle at reference time [rad]

$$\Omega = \Omega_o + (\dot{\Omega}_o - \dot{\Omega}_e)\, t - \dot{\Omega}_e\, t \qquad (2.26)$$

Ω = corrected right ascension of ascending node [rad]

Ω_o = right ascension at reference time [rad]

$\dot{\Omega}_o$ = rate of change of right ascension [rad/s]

4. *Computation of Satellite Position in ECEF*

Equations 2.27 and 2.28 are used to compute the position of the satellite in its orbital plane (Mueller, 1964, pp. 147-170; Van Dierendonck et al, 1980, pp. 67):

$$X^1 = r \cos U \qquad (2.27)$$

$$Y^1 = r \sin U \qquad (2.28)$$

X^1 = position in orbital plane [m]

Y^1 = position in orbital plane [m]

Equations 2.29 and 2.30 are used to compute the position of the satellite in ECEF:

$$X_{sat} = X^1 \cos \Omega - Y^1 \cos I \sin \Omega \qquad (2.29)$$

$$Y_{sat} = X^1 \sin \Omega + Y^1 \cos I \cos \Omega \qquad (2.30)$$

$$Z_{sat} = Y^1 \sin I \qquad (2.31)$$

X_{sat}, Y_{sat}, Z_{sat} = ECEF of satellite coordinate, WGS-72 [m]

D. LEAST-SQUARES ADJUSTMENT (ITERATIVE METHOD)

The corrected pseudorange between an unknown station P and the satellites is given by Jorgensen (1984):

$$R_{cor} = R_{tru} + c\,(\delta t_u - \delta t_{sv}) \qquad (2.32)$$

where:

R_{cor} = corrected pseudorange from Satellite Vehicle (SV) number k to the unknown station P

R_{tru} = true pseudorange from Satellite Vehicle (SV) number k to the unknown station P

$$D = [(X_{sat}-X\ )^2 + (Y_{sat}-Y\ )^2 + (Z_{sat}-Z\ )^2]^{1/2} \qquad (2.33)$$

D = the preliminary distance between SV to the unknown station P.

$X_{sat} Y_{sat} Z_{sat}$ = the coordinates of SV [m]

X_o, Y_o, Z_o = the preliminary coordinates of the unknown station P [m]

c = the velocity of light in vacuum [m/s]

The corrected pseudorange may be linerized by a Taylor series expansion as:

$$R_{cor} = R_{cal} + \frac{\delta R|}{\delta X|}\Delta X + \frac{\delta R|}{\delta Y|}\Delta Y + \frac{\delta R|}{\delta Z|}\Delta Z + \frac{\delta R|}{\delta t|}\Delta t$$

where the Jacobian of R calculated for δX, δY, δZ, and δt are

$$B = \left| \begin{array}{cccc} \frac{\delta R}{\delta X} & \frac{\delta R}{\delta Y} & \frac{\delta R}{\delta Z} & \frac{\delta R}{\delta t} \end{array} \right|$$

or

$$\left| \begin{array}{cccc} \frac{X_o-X_{sat}}{D} & \frac{Y_o-Y_{sat}}{D} & \frac{Z_o-Z_{sat}}{D} & c \end{array} \right|$$

where:

R_{cal} = calculated pseudorange by preliminary coordinates of P from SV to the unknown station P [m]

The least squares adjustment may be done by the iterative method. The observation equation matrix:

$$\Delta B + v = f \tag{2.34}$$

$$f = R_{cal} - R_{cor} \tag{2.35}$$

where

B = the Jacobian matrix, n by 4.

Δ = the correction of the unknown coordinates matrix, 4 by 1 matrix; consists of δX, ΔY, ΔZ, and Δt

v = the residual observation matrix, n by 1

f = the difference between range corrected and range calculated by a priori coordinates matrix, n by 1

W = the weight matrix, n by n

$w = 1/\sigma$; σ is the variance of the observations

n = number of observations, minimum 4 observations

R_{cal} = calculated pseudorange matrix by preliminary coordinates of P from SV to the unknown station P

R_{cor} = corrected pseudorange matrix SV from the unknown station P

Minimizing Equation 2.34 as is done by Mikhail and Ackerman (1974)

$$N = B^T W B \tag{2.36}$$

$$t = B^T W f \tag{2.37}$$

$$\Delta = N^{-1} t = (B^T W B)^{-1} (B^T W f) \tag{2.38}$$

X_P, Y_P, Z_P = the corrected coordinates of the unknown station P [m]

$$X_P = X_o + \Delta(1) \tag{2.39}$$

$$Y_P = Y_o + \Delta(2) \tag{2.40}$$

$$Z_P = Z_o + \Delta(3) \tag{2.41}$$

$$\delta t_u = \Delta(4) \tag{2.42}$$

X_o, Y_o, Z_o = the preliminary coordinates of the unknown station P [m]

Δ = estimator of reference variance matrix

$\Delta(i)$ = element of matrix Δ [m]

E. KALMAN FILTER

Meyerhoff (1985) gave a method for the computation of dynamic positions by means of an eight-state Kalman filter after pseudoranges have been corrected and smoothing has been applied to them by Doppler count. The computation of position consists of computation of corrected pseudoranges, satellite's positions, variance of pseudoranges, Jacobian matrix B, Kalman gain (K), updated position, and the updated covariance matrix (P). [For details of the Kalman filter see Meyerhoff (1985), Bierman (1982), and Brown (1983)]. The variances of the pseudoranges are computed from the variance pseudoranges of L1 and L2. The variances of the pseudoranges of L1 and L2 are

$$V_{L1} = K_2 + K_1 \left[\frac{\beta_L \quad n}{10^{C_{L1}}} \right] \left[0.5 + \frac{\beta_D}{10^{C_{L1}}} \right] \tag{2.43}$$

V_{L1} = variance of pseudorange data for L1 or L2, respectively at timetag [s²]

$K_1 \& K_2$ = variance bias factors [s²]

β_L = code loop noise bandwidth

n = number of trackers

C_{L1} = 0.1 of carrier power to noise density of L1

C_{L1} = 0.1 of carrier power to noise density of L2

β_D = code predetection bandwidth

The variance of pseudorange is computed by:

$$V_{psd} = [V_{L1} + (V_{L1} + V_{L2})] / [(Q_1/Q_2)^2 - 1]^2 \qquad (2.44)$$

V_{psd} = cariance of pseudorange [s^2]

$\Sigma(k,k)$ = V_{psd} for tracker k, respectively

$$K = P(-)\, B^T (B\, P(-)\, B^T + \Sigma)^{-1} \qquad (2.45)$$

K = Kalman gain matrix

Σ = variance of pseudorange matrix

B = Jacobian matrix

P(-) = The covariance matrix before updated of this data point, the initial value is the initial variance of X , Y , Z , δt ; of diagonal are zero

$$P(+) = P(-) - K\, B\, P(-) \qquad (2.46)$$

P(+) = The updated covariance matrix

$$R_{omc} = R_{obs} - R_{cal} - c\, t_{cor} \qquad (2.47)$$

R_{omc} = pseudorange range residuals [m]

R_{obs} = pseudorange observed [m]

R_{cal} = pseudorange calculated [m]

t_{cor} = correction of pseudorange [m]

c = speed of light [m/s]

$$X(+) = X(-) + K(1)\, R_{omc} \qquad (2.48)$$

$$Y(+) = Y(-) + K(2)\, R_{omc} \qquad (2.49)$$

X(-) = X coordinate before update [m]

$$Z(+) = Z(-) + K(3)\ R_{omc} \tag{2.50}$$

$$\delta t(+) = \delta t(-) + K(4)\ R_{omc}/c \tag{2.51}$$

$Y(-)$	= Y coordinate before update	[m]
$Z(-)$	= Z coordinate before update	[m]
$\delta t(-)$	= receiver clock offset before update	[s]
$K(i)$	= row i of matrix K	
$X(+)$	= The updated X coordinate	[m]
$Y(+)$	= The updated Y coordinate	[m]
$Z(+)$	= The updated Z coordinate	[m]
$\delta t(+)$	= The updated receiver clock offset	[s]

III. THE TI-4100 TEST IN MISSISSIPPI SOUND

A. FIELD OPERATION

The U.S Naval Oceanographic Office (NAVOCEANO) conducted a test on Mississippi Sound in May 1984 to evaluate the performance of the TI-4100 on a marine platform (small launch) and to determine whether the TI-4100 is adequate for hydrographic surveying. The launch position was determined by a GPS receiver and four Del Norte Trisponders on shore stations; two of the Trisponders were located above second-order conventional North American Datum-1927 (NAD-27) bench marks, while the other two Trisponder positions were determined by means of the TRANSIT SYSTEM (Dupont and Dunn, 1984, pp. II-49 and II-50). One TI-4100 was on the launch and one was at a third NAD-27 bench mark. Three first-order bench marks were observed by a TRANSIT receiver to determine the local datum shift from NAD-27 to WGS-72 (Dunn, 1985).

Data for 1984 Julian days 136 and 138 collected during the NAVOCEANO test were arranged in standard GPS data exchange format (Scott and Peters, 1983, pp. 3-23) and sent to NPS for study. The GPS shore station data and Trisponder data were stored on a single data tape. The GPS shore station data were acquired every 12 seconds, and the Trisponder data were acquired every second. The launch receiver's raw GPS data (consisting of pseudoranges, pseudorange-rates, satellites ephemerides; timetag and atmospheric data) were acquired and recorded every second; the launch's real-time positions as determined by GPS (X, Y, Z and δt) were acquired every 6 seconds; and both the raw data and real-time positions were stored on three additional tapes.

B. DATA PROCESSING

NSWC has four computer programs for post-processing raw GPS data into the receiver's position and clock offset. The first program is called CON9TR; the second SOLTOM; the third KALMN2; and the fourth program DOALL. The first converts data from the standard data exchange format to a new format compatible with the second and third programs. The SOLTOM and KALMN2 programs convert the output data of CON9TR into ECEF coordinates by least square adjustment or by eight-state Kalman filtering, respectively. DOALL compares dynamic post-processed data with the Trisponder position data in UTM coordinates. The programs were written by Meyerhoff (1985) for the Computer Data Corporation Cyber-175 and in their entirety are quite large. I was not able to convert these programs for the NPS IBM-3033 due to their complexity and size.

The data from GPS time 185000 s to 188600 s (Δt = 3600 s) on 1984 Julian day 136, was converted from standard 9-track tape to a new format, so that it would be compatible for further processing by the least squares adjustment or Kalman filter computer program.

For the 3600-s interval for which shore station data were analyzed using the least squares adjustment program, the positions obtained by post-processing did not significantly differ from real time positions.

For the 3600-s interval for which GPS and Trisponder launch positions were analyzed, a total of 3171-s data points from both positioning systems were available. The launch positions determined by GPS consisted of 2740-s of data points based on four satellites and 431-s of data points based on three satellites. The positions of the launch determined by GPS were post-processed using the Kalman filter program and compared with the launch positions determined by Trisponders. Since the time tags of the shore station's GPS positions differ from the launch's, further differential mode post-processing of this data was not done.

The post-processing for GPS shore station positions and launch positions used broadcast ephemerides. Post-orbit ephemerides were not available to possibly improve the accuracy.

C. ACCURACY OF LAUNCH POSITION DETERMINED WITH TRISPONDERS

The "true" position of the launch was computed by least squares adjustment from the two second-order shore stations (NAD-27) and the two TRANSIT stations in WGS-72 using the four ranges from the Trisponders. The two second-order shore stations (NAD-27) were transformed to WGS-72 and converted to UTM. The two TRANSIT stations in WGS-72 were converted from ECEF to UTM. The total accuracy of the launch's position determined by the Trisponders is ± 7 m, a value which depends on the accuracy of the Trisponder locations and the accuracy of the Trisponders themselves; Table I shows the computation.

TABLE I

THE TOTAL ACCURACY OF THE LAUNCH'S POSITION DETERMINED BY TRISPONDERS

The accuracy of transformation	=	± 6 m
The accuracy of Trisponder	=	± 3 m
The accuracy of convertion to UTM	=	± 1 m
The accuracy of Transit	=	± 1 m
The rms accuracy of the launch position determined by Trisponder	=	± 6.86 m

The accuracy of the launch's position determined by the Trisponders depends on the accuracy of the position of the two second-order Class 2, shore stations used as Trisponder sites locations. For a conventional geodetic station Bossler (1984) gives second-order accuracy as 1:20,000. The length of a side is generally not less than 5000 m, and the standard deviation of angle observation does not exceed 0.8". Thus, the position accuracy of the second-order shore station sites is approximately ± 0.25 m. The accuracy of the transformation from NAD-27 to WGS-72 was determined by datum shift. The datum shifts were determined locally by TRANSIT observations on three first order NAD-27 stations. The root-mean-square accuracy of the transformation may be estimated as approximately 5 to 10 m (Kumar, 1985). The accuracy of conversion from WGS-72 to UTM coordinates may be assumed ± 1.0 m (Kumar, 1985; U.S Army, 1973, pp. 8-9)

The accuracy of the launch's position determined by the Trisponders depends also on the position accuracy of the other two shore stations determined by TRANSIT satellite observations. The accuracy of the TRANSIT stations may be assumed to be ± 1.0 m, since observations from more than 25 passes were used, and precise ephemerides were applied (Bossler, 1984, pp. 3-10 and 3-11; Kumar, 1985).

Because the Trisponder is a microwave positioning system, it is subject to multipath errors and range holes. In general the accuracy of a Trisponder is ± 3 m (Umbach, 1981, pp. AD-2), although it might be larger in some environments. Because the Trisponder observations were made at night during satellite passes, the accuracy of the test data may be better than ± 3 m.

D. ACCURACY OF THE LAUNCH'S POSITION DETERMINED BY THE GPS RECEIVER

The GPS post-processing position values were compared with the launch's position determined by the Trisponders, and the mean of the rms values was found to be less than ± 11 m if four satellites were available (Table II). Positions for the first three seconds were poor, with the maximum rms difference being 215 m. The mean of the rms values was found to be less than ± 21 m if only three satellites were available (Table III).

The signal quality of satellite number 8 was variable; this was indicated by bad pseudorange residuals, which caused an increasing of the northing, easting and rms differences. The signal quality of satellite number 8 tended to be cyclic, decreasing until it was lost, leaving only 3 satellites, and then increasing again, making four satellites available again. The signal quality is measured by the pseudorange

TABLE II

DIFFERENCE BETWEEN GPS- AND TRISPONDER-DETERMINED POSITIONS WITH FOUR SATELLITES IN VIEW

	Mean	Maximum	Minimum	Sigma
rms	10.677	28.733	0.422	12.735
Easting	-7.058	12.751	-25.622	10.653
Northing	2.136	25.445	-19.429	6.854

residuals, which are considered bad when exceeding 20 m. A total of 865 available data points indicated bad pseudorange residuals, which were the result of bad Doppler counts. The number of bad Doppler counts were: 1 from satellite no. 6, 1 from satellite no. 3, 97 from satellite no. 11, and 766 from satellite no. 8.

The presence of the four "good" satellites and four good pseudoranges will significantly improve the accuracy.

TABLE III

DIFFERENCE BETWEEN GPS- AND TRISPONDER-DETERMINED POSITIONS WITH THREE SATELLITES IN VIEW

	Mean	Maximum	Minimum	Sigma
rms	20.538	133.621	0.765	27.538
Easting	-15.920	12.132	-125.801	25.193
Northing	-1.614	32.296	-45.040	11.120

The accuracy of the launch's position determined with the Trisponders is better than the launch's position determined with GPS. Although 29 percent of the data have similar accuracy, further studies to separate good data may be performed. The TI-4100 does not, however, have the distance limitation of the Trisponders: It is limited only by the present coverage of GPS satellites.

The real-time dynamic positions were compared with position determined by post-processing. The mean position differences were ΔX= 80 m, ΔY= 7 m, and ΔZ= 13 m.

IV. CONCLUSIONS

1. The overall accuracy of Trisponder-determined positions for this study was ± 7 m. As the observed range increases, the accuracy of positions obtained from the Trisponders decreases. Beyond line-of-sight Trisponders cannot be used.

2. The accuracy of ship positions determined at sea by a TI-4100 GPS receiver is slightly lower than the position accuracy obtained with shore-based Trisponders, although 29 percent of the data analyzed have similar accuracy. The GPS receiver is more versatile than the Trisponder system in that GPS is not limited by line-of-sight. Post processing accuracy may be improved if post-orbit ephemerides data were available for the analysis.

3. To improve the position accuracy by GPS receivers, further studies in a differential mode should be performed in the marine environment.

4. The main difficulty of this study was the complexity of the programs for the CDC computer. The conversion of the NSWC computer program to the NPS IBM-3033 is suggested for the further application at NPS. A collection of hydrographic subroutines in a common library at NPS would be very helpful in future hydrographic studies at NPS.

APPENDIX A
ABBREVIATIONS AND ACRONYMS

AFP	=	Approval for Full Production
C/A-code	=	Coarse and Acquisition code
CDC	=	Computer Data Corporation
DSARC	=	Defense System Acquisition Review Council
DT&E	=	Development Test & Evaluation
ECEF	=	Earth Centered Earth Fixed
FNOC	=	Fleet Numerical Oceanography Center
GDOP	=	GEOMETRIC Dilution of Precision
GPS	=	Global Positioning System
IBM	=	International Business Machine
IOT&E	=	Initial Operational Test and Evaluation
JPO	=	Joint Program Office
MHz	=	Mega Hertz
NAD-27	=	North American Datum 1927
NAVOCEANO	=	U.S Naval Oceanographic Office
NPS	=	Naval Postgraduate School
NSWC	=	Naval Support Weapon Center
P-code	=	Precision code
rms	=	root mean square
SEP	=	Spherical Error Probability
SV	=	Satellite Vehicle
Timation	=	Time and Navigation
USN	=	United States Navy
UTM	=	Universal Traverse Mercator
VLBI	=	Very-Long-Baseline-Interferometry
WGS-72	=	World-Geodetic-System 1972

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